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Report No. 180

MATERIALS APPLICATIONS BRANCH

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STUDY OF RELATIONSHIPS BETWEEN PROCESSING VARIABLES AND PROPERTIES IN THERMOPLASTIC INJECTION MOLDED PARTS
Selection of Specimen and Process Variables, Mold Design, Instrumentation and Molding Procedure

by

F. A. McLaughlin

15 January 1973
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MATERIALS ENGINEERING DIVISION

FELTMAN RESEARCH LABORATORY

changed to Applied Science Div

Picatinny Arsenal, Dover, New Jersey

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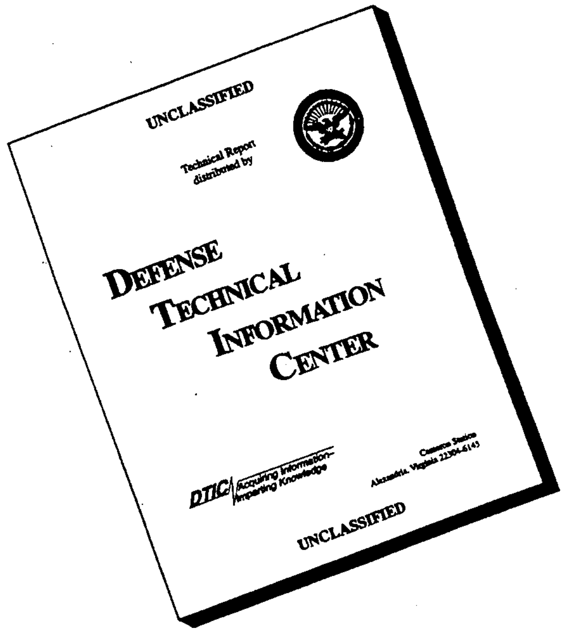

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Acknowledgement

The author wishes to acknowledge the contributions of Mr. S. Marhefka in the operation of the injection machine.

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OBJECTIVE

To investigate the relationship between injection molding process variables and the physical and mechanical properties of thermoplastic material in injection molded plastic parts. This will be accomplished by developing the techniques, adapting instrumentation and assessing changes in material characteristics.

BACKGROUND

The American plastics industry has been steadily growing since James Hyatt's work with cellulose nitrate more than 100 years ago. The volume of plastics produced has increased extensively and the demand is still continuing. Today, in particular, quality plastic parts are in greater demand than ever before by industry because of their use in engineering applications. This is also true in the military, where plastics are being used in more and more applications. These military plastic applications include such items as housings, gears, mine components, fuze components and grommets. The use of plastic materials is based on their chemical resistance, lightweight, ease of fabrication, noncritical material category, nonmagnetic characteristics, and in most cases, lower cost. All these applications require high quality to perform their function over the long life cycle. In the military as well as industry, designers are hampered by lack of complete knowledge on the effects of processing on the properties of molded items. As a result, those items that are plastic are usually over-designed, resulting in increased weight and cost.

Even with over-designed items performance may be affected by lack of production control. In this connection there is difficulty in the control of plastic part quality on "procurement buys" by the military because the tools to evaluate part quality or assure performance are not readily available. Although some work has been done, additional efforts are necessary to enable the more effective design and manufacture of plastic parts. In this respect, this Division submitted a program to investigate the relationship between injection molding process variables and the properties of molded thermoplastic items. The program was approved by Army Materiel Command (AMC) and funded as Project 56202-Subproject #4, with administrative control by Frankford Arsenal.

INTRODUCTION

The investigation of the relationships between the processing variables and properties of thermoplastic molded parts was divided into several parts, i.e., a processing variable specimen selection; mold design; instrumentation; test methods evaluation and procedure development; and specimen test and evaluation. This report covers the processing variable selection, mold design, instrumentation and specimen selection portion, and the specimen testing and data evaluation.

This Division reviewed previous work in the processing field by means of a literature search and interviews with cognizant persons in industry. A specimen design was selected and a mold was designed and fabricated. An instrumentation system was developed to record the selected processing

variables. Materials were selected and a procedure developed to mold test specimens. This report contains a discussion of the technical approach and rationale in each of these areas.

DISCUSSION

In order to insure that the efforts of this Division would not be a duplication of previous published or unpublished work, a background study was initiated. The results of this study were used as a foundation upon which work on developing additional information on processing effects was instituted. One part of the study was a literature search conducted by the Plastics Technical Evaluation Center (PLASTEC), Picatinny Arsenal, with a second effort being personal visits to cognizant individuals[2] in the plastics field.

The literature search revealed that a great deal of work has been done in the area of injection molding and mold design. However, most of the processing work used standard injection machine instruments for control and recording of processing parameters such as pressure and temperature. Due to the nature of these standard instruments and their machine locations, the investigators actually had records of machine parameters and not that of the actual polymer material. The investigators, in essence, did not know what the polymer was seeing in terms of pressure and temperature. In many cases the transfer of machine readings to polymer readings was done by rough rules of thumb, a procedure which is not very accurate.

Recent work published by Mr. D. Paulson[3] has produced pressure sensing instruments that enable investigators to easily record polymer melt pressure

inside the mold during the injection cycle. Mr. Paulson uses the pressure readings in the mold as part of a closed circuit feedback system for controlling the machine injection pressure during molding. His work has been directed mainly at improving the ability to control machine injection pressure from cycle to cycle as an aid in the control of past production.

Interviews with personnel from E. I. DuPont, E. E. Bliss, Dow Chemical, G. E., U. S. I., and BASF[2], revealed a great interest in this type of program. None contacted knew of any similar effort being conducted at this time. It was felt that this type of program was badly needed by the plastic industry as well as the U. S. Government. The results of this program could benefit both the buyer and the molder of plastic items.

The technical discussions and approaches described herein are the result of consultations with industrial experts and the engineering judgment of knowledgeable military specialists.

Process Variables

Prior to any instrumentation selection or mold designing, a critical review of the injection molding process was made. This review revealed the many parameters involved in molding a component. It was concluded that in order to obtain worthwhile information all of the variables could not be investigated within the present program. Thus the many program variables were divided into three separate but interdependent areas in order to determine those most amenable parameters to investigate in a practical program. The three areas were the machine, the material and the molded part. The major machine variables primarily concern pressure,

temperature and time; but the specific machine settings considered were as follows:

1. Injection Pressure
2. Holding Pressure
3. Back Pressure
4. Screw RPM
5. Material Cushion
6. Injection Cylinder Temperatures
7. Material Temperature at the Nozzle
8. Mold Temperature
9. Injection Time
10. Plunger Forward Time (Holding Time)
11. Mold Open Time
12. Mold Close Time
13. Cooling Time

The material variables included:

1. Melt Index
2. Apparent Viscosity
3. Molecular Weight
4. Crystallinity
5. Molecular Weight Distribution (MWD)

The part variables included:

1. Part Size
2. Part Weight
3. Part Configuration

An assessment of each of the listed machine variables was conducted to determine those variables to be investigated during this program. In the selection of the variables to be studied consideration was made as to those items that are normally varied by molders that have direct influence on the polymer during processing. One of the variables selected was that of injection pressure. Injection pressure is a commonly varied parameter by the molder. While its effects on part properties are not fully understood they are related to "residual pressure" in the molded part and thus is recognized as one of the most important variables in the injection cycle. As indicated by the following equation for polymer flow through a round passage a change in O.D. is directly related to the flow rate of a polymer.

$$Q = \frac{R^4 \pi \Delta P}{8\ uL}$$

where

Q = flow rate (in^3/sec)

R = passage radius (in)

ΔP - pressure drop through passage (psi)

u - apparent viscosity of material ($lb\text{-}sec/in^2$)

L - flow passage length (in)

Pressure as seen in the equation is also related to the viscosity of the material and passage size. Pressure is therefore of prime concern since minimum losses are desired through the nozzle and mold. Pressure will also affect the final part dimension and weight as will be discussed later in this report. It will also influence the degree of

orientation within a polymer during the injection phase of the molding cycle which in turn influences the amount of orientation within the part after the injection cycle is completed.

A second variable selected for investigation was that of polymer melt temperature. From experience most molders recognize that changes in polymer temperature will produce differences in polymer viscosity. This in turn will affect the flow rate of the polymer as shown by relationship of viscosity to flow rate in the flow rate equation for polymers through passages. However it is not fully known what is the magnitude of effect that changes in melt temperature have on the material.

The third variable selected for study was mold temperature. Mold temperature changes affect the rate of cooling of the polymer during the injection phase which will affect the melt viscosity and thus the flow rate and pressure drop. Mold temperature changes will also affect the cooling rate of the polymer during the cooling phase of the molding cycles which may affect the degree of orientation and of residual stress in the molded item.

The three variables to be considered, pressure, melt temperature and mold temperature (cooling rate), are also interrelated during the cooling phase of the molding cycles as shown by a simplified version of Vander Waals equation:

$$(P + \pi)(V - W) = RT$$

where P = polymer pressure

T - polymer temperature

V - specific volume

π, R, W - are constants for the specific polymer.

This equation states that when T is a constant P and V are inversely related. This situation is approximated in the mold cavity during the packing phase which occurs after the cavity is filled. When V is constant then P and T are directly related. This situation occurs after gate seal has been completed and the polymer melt is cooling.

Pressure during the packing stage plays an important role in determining the weight of the part, pressure in the cavity after gate "seal off" has been completed affects the post mold shrinkage of the part and the internal stress levels of the part[6]. The density of any given polymer at room temperature is a constant. However, due to packing, the polymer is slightly compressed. Upon cooling, the polymer seeks its original room temperature density. If during cooling, the polymer is unable to move in the mold, then stresses are built-up in the part and upon release from the mold the part may change dimensions as the stresses are relieved. However if the part stresses are not relived they may result in premature part failure. Variations in the packing pressures cause variations in cavity pressure which result in variations in internal stress levels in the part. If just prior to mold opening, the cavity pressure is high, then the part will have a high stress level and will tend to expand upon ejection from the mold. If the cavity pressure is low, the part will have little or no stress and will tend to remain constant or shrink when ejected. Different pressure at different locations in the cavity may cause the molded part to shrink and/or expand nonuniformily when ejected and produce a part that is warped.

It should not be inferred that pressure is the only cause for internal stress and resulting dimensional changes. Temperature and molecular orientation also play important parts in determining stress levels. No attempt is made to rank these parameters as to their importance in developing internal stresses. More detailed discussions of these parameters are readily available in the published literature,

As with most materials, the volume of thermoplastics increases as temperature increases, i.e., as temperature increases the density decreases. Therefore when a polymer is in the melt stage its density is less than when it is a solid at room temperature. As a polymer melt cools it will return to its room temperature density. If the melt is restricted, as in a mold cavity while cooling, then internal stresses will be developed. Upon ejection from the mold, the part may deform in relieving these stresses. This stress relieving may occur immediately or may take some time. Thus what appears to be a good part at the injection machine may sometime later warp or crack due to the stress relieving process.

Coupled with and affected by temperature and pressure is molecular orientation. Polymer molecules consist of repeating groups of monomer unit which are very long in comparison to their width. Under normal conditions the molecular chains curl and twist in a random pattern and the properties are isotropic. Alignment of the chains results in an increase in strength parallel to alignment and a decrease in strength perpendicular to alignment. Internal stresses are produced as the aligned chains try to return to their random curled positions. This molecular orientation or

alignment is induced as the polymer flows through the nozzle and mold passages during molding. In injection molding, force is applied to the polymer melt in order to have it flow into the mold cavity. A typical polymer velocity profile is illustrated in Fig 1. It is the flow profile that is the source of the phenomenon of molecular orientation in injection molding of polymers. As the figure shows the velocity varies across the profile. The velocity being zero at the wall and increasing toward the center area. Around the center area the velocity is constant. It is this velocity variance that causes the molecular chains to orientate in the flow direction. Orientation occurs because the molecular chains must become aligned in a constant velocity stream, i.e., two ends of the same chain cannot flow at different velocities. The only way an entire chain can flow at the same velocity is for the chain to align itself along a given velocity stream. When the mold cavity is filled and flow has creased the molecular chains tend to return to their natural random configuration. Given enough time at an elevated temperature, this return to random will be accomplished with resulting zero internal stress. However if polymer cooling is rapid, which is usually the case, many of the molecular chains will be "frozen" in their orientated configuration. A subsequent exposure to sufficient elevated temperature will allow the chains to move and become random again resulting in possible part dimension changes. As the mold cooling gradient is from the cavity wall inward, the resulting part will exhibit frozen orientation near the outer surfaces with decreasing orientation toward the center of the part.

One of the characteristics that makes polymers difficult to study is its viscoelastic nature. That is, the material will exhibit characteristics of both a fluid and a solid.[8] When a polymer is in the melt stage it exhibits viscous behavior. Thus any change in orientation or material is relatively easy to accomplish with resulting low stresses involved. However as the polymer solidifies, it takes on a more elastic behavior and a small change in orientation or material movement now will meet greater resistance and resulting higher stress levels.

From this discussion it can be concluded that the factors responsible for internal stresses in molded parts are many and their actions on the material during molding are complicated and to varying degrees interdependent. It was beyond the scope of the program to study each variable and its effect on the internal stress level of a molded part. Therefore the three variables discussed above, pressure, melt temperature and mold temperature were selected for study in this program. In addition screw location and hydraulic pressure were to be monitored. The purpose of monitoring the hydraulic pressure was to establish whether any variations found in melt pressure was due to hydraulic system variations. Screw location was monitored in order to insure consistent shot size.

Instrumentation

As a result of the variable study, the key machine parameters to be determined were specified. This necessitated that the instrumentation developed be adaptable to an inhouse injection molding machine. The injection machine used for this program was a New Britain Machinery Co. 10 oz screw machine with a hydraulically actuated mechanical clamp of 175 tons.

The machine has three temperature zones on the barrel, each controlled by in-barrel thermocouples and Barber-Coleman controllers. The hydraulic system supplies both a high and low pressure to the screw by means of timer actuated solenoid valves. Generally the higher pressure is for injection and the low pressure is for holding. Both pressures are set using one dial gage. Normally pressure readings are taken from a dial gage mounted in the hydraulic line. This reading indicates the pressure acting on the injection cylinder and is used to calculate the melt pressure in the barrel. This current procedure is a poor method to obtain nozzle injection pressure because mechanical losses are not considered and secondly, the calculations to obtain polymer melt pressure do not take into account differences between polymers as to their compressibility.[4] The gage gives only a peak reading and not a pressure time curve. Injection times are also so short that it is very difficult to read the dial gage accurately and in addition the current procedure does not give pressures within the mold. The actual presure in the mold cavity could be much lower than that in the barrel due to pressure drops in the nozzle and runner system.

For this program, three pressure locations were decided upon: 1) hydraulic line pressure, 2) nozzle melt pressure, and 3) mold cavity pressure. Standard equipment was available for sensing the machine pressure. Hydraulic line pressure was monitored by means of adapting a standard Dynisco Div. of Microdot Inc. hydraulic pressure transducer (Fig 2) at the existing dial gage location. The melt pressure transducer was located in the nozzle directly opposite the melt temperature thermocouple. This transducer was a specially shortened strain gage type manufactured by Dynisco Div. of Microdot Inc. (Fig 3). The transducer utilizes a capillary tube to transmit the pressure on a flush diagram to the bonded strain gages mounted in the pressure housing. The transducer has an internal shunt for calibration which simulates 80% full scale output.

Over the years difficulty had been encountered in measuring cavity pressure. In the mid 50's Krol[10] used strain gages bonded to an ejector pin to measure cavity pressure. Difficulty was experienced in keeping the gage lead wire from breaking during mold cycling. Conventional pressure transducers were used by Spencer and Gilmore in the early 50's and by Prosen and Johnson[12] in the early 60's to measure cavity pressure. With this approach, the transducers were either bolted or threaded to the mold and removal required complete mold disassembly. Both efforts were expensive and prone to error due to temperature. In mid 1969, Control Process Inc. marketed a slide transducer for measuring cavity pressure.[13] This transducer uses knockout pins as the pressure transfer agent (Fig 4). This transducer has several advantages over either the strain gages, pins or the threaded transducers. It is a rugged transducer with the sensing element encased in a steel bar. It is portable and reusable, i.e., it can easily

be removed from one mold and placed in another without disassembling the molds. It is not troubled with temperature induced error because of the use of the knockout pin as the force transfer agent. This is the type of transducer that was used in the program.

Present industry practices are to use standard machine temperature controllers for control of melt temperature. These controllers actually measure the temperature of the metal barrel and not that of the plastic. Most molders use an "experience factor" in determining actual melt temperature. A common procedure for checking melt temperature is injecting the polymer melt into a container and measuring the temperature using a needle pyrometer. These methods give only a rough estimate of the actual polymer melt temperature and differences between machines make it extremely difficult to transfer temperature settings from machine to machine.

The more desirable method is to insert a probe through the nozzle of the barrel into the polymer melt. This way the melt temperature could be read directly. The thermocouple probe would have to be sensitive enough to sense small temperature changes occuring during flow while withstanding the melt injection pressures without damage. Such a probe was available from West Instrument Corp. (Fig 5) and readily adapted to a conventional nozzle. Although the adaption was available there was no known use of nozzle melt sensing, particularly in polymer research molding studies.

Another important location for melt temperature readings is in the mold cavity. Temperature readings in this area were considered important because temperature has an effect on internal stress in molded parts. In discussions with researchers, with respect to temperature readings within

the mold, it was made known that there would be inherent problems in measurement due to the problem of flow and nonuniformity which exist in a mold. Regardless, an attempt was made to obtain such readings.

Cavity temperature sensors could be one of two basic types: thermocouple or thermistor. The two types are similar in performance characteraitics. The most important characteristic required for this program was speed of response. The factors that affect the response rate of a temperature probe are: 1) the mass of the probe surrounding the sensitive point; 2) thermoconductivity of the transducer materials; 3) mass and conductivity of measured fluid; 4) velocity of fluid over probe. Therefore, it is obvious that a probe with a small diameter made of highly conductive material will respond most rapidly to temperature changes. Since thermocouple materials have shorter conductive paths, a thermocouple will respond more rapidly than a thermistor of equal diameter. For a .062 diameter probe the thermo couple can be three times as fast as a similar thermistor.[9] The thermocouple used in the program was a grounded .062 O.D. probe with the tip reduced to .040 O.D. The probe was a standard unit obtained from the Conax Corp.

The key element in the measurement of the pressure and temperature parameters is the recording equipment. To aid in determining what was required, an analysis of the injection cycle from a recording viewpoint was made. Polymers in the melt stage are characterized as being highly damped. Therefore high frequency response equipment is not required. Total injection cycle could be anywhere from 20 sec. to 5 min. But, for this program, the total cycle will be about 30 sec. with actual injection taking about 3/4 sec.

Injection pressure goes from zero to 18,000 psi within 3/4 second. Therefore rapid trace writing and rapid chart speed are required.

As a result of the injection cycle analysis a list of requirements for the recording system was developed and is listed below.

1. Compatible with transducers and thermocouples.

2. Easily calibrated and stable.

3. Readout trace must be easily read and durable enough for filing for future use.

4. Flat frequency response must be adequate.

5. System must be portable, easy to maintain, operate, compact and rugged.

6. Chart speed such as to record total injection cycle.

7. Adaptable for studying other polymer processes.

8. Compatible with existing laboratory equipment.

9. Minimum of 12 active channels with room for additional as required.

10. Low cost.

11. All sensor outputs should be fed into one complete recording system.

Due to the transient nature of the injection variables a strip chart recorder was required. There were two types available: direct writing and light beam. The direct writing type utilizes a stylus to write, similar to a pen writing on paper. The stylus and ink system can be either pressurized or non-pressurized. Each channel requires a separate stylus. The trace is immediately readable and will not fade. Charts speed up to 8 in/sec and maximum frequency response over full span width of 60HZ are available. Due to the mechanical nature of the writing system, the traces

are not able to cross each other thus limiting the trace span for each channel. Six channels per strip is the maximum now available. Relatively high inputs are required to drive the mass of the stylus.

The light beam type relies on the etching of a special chart paper by ultraviolet light to produce a trace. The ultraviolet light is focused and positioned by a galvanometer with one galvanometer per channel. The galvanometer is a device for the measurement of current and voltage variation. A change in input causes the galvanometer mirror to move, which in turn causes the reflected ultraviolet light beam to move on the paper. The galvanometer requires relatively low inputs because the mass involved is low. The trace is legible after about 30 seconds exposure to standard room light. Being light sensitive, the trace must be stored in an unlighted area such as a filing cabinet to prevent fading. Chart speeds of 120 inches per second and maximum frequency response over full span with 4800 Hz are available. Maximum span width for all channels is the width of the chart. This is due to the ability of the traces to cross each other. The maximum number of channels per chart is 36. Both types of recorder are available with trace identification, power take-up units and timing marks.

The recording systems were evaluated in light of the injection cycle analysis and the system requirements. Both systems are compatible with the transducers and thermocouples, easily calibrated, have little or no drift, have adequate frequency response, portable, easily maintained, easily operated, compact, rugged and able to record entire cycle. The direct

writing system produces instant non-fade traces. The light beam system requires a short delay between etching and reading and the trace is prone to fade when exposed to light. The light beam system has a wider range of frequency responses and chart speeds available than the direct writing system. Trace span width for each channel is the width of the chart with light beam systems. Maximum channels per chart is 36 with light beam systems and 6 to 8 with direct-writing systems. The cost of a 12 channel light beam system was considerably less than a 12 channel direct writing system. The cost of additional channels was also less with the light beam system. The decision was to purchase a light beam system. The system consisted of a Honeywell Model 1508 Visicorder with Accudata 105 Gage Control Units and Accudata 106 Thermocouple Control Units (Fig 6).

In addition to the pressure and temperature instrumentation as discussed above a linear variable displacement transducer (LVDT), Fig 7, was mounted on the injection machine to monitor and record screw travel and location. The LVDT was also used to monitor the amount of melt cushion during molding.

Control of mold temperature was done by means of Sterlco temperature control unit Model 6002. This unit uses water for maintaining the mold temperature. The controller thermocouples read water temperature at the unit, not at the mold. This is a standard industrial type and suitable for program needs, and did not require any modifications.

Mold Design

The most practical approach in mold design involved the use of a mold base with an insert for each specimen design. A gate insert was also

incorporated into the mold thus enabling changing the gate size and location with a minimum of cost and time. The initial gate dimensions, runner size and length were selected based on good mold design practice. Sensing instrument locations were selected to give pressure drop through the gate and pressure-temperature profiles in the cavity (Fig 8). The locations before and after the gate would also be used to determine gate "freeze-off" which would determine holding pressure time.

A major design problem was the incorporation of pressure and temperature sensing instruments at each of the selected locations in the cavity. It was desirable to record both pressure and temperature at the same location. As previously mentioned, it was decided to use ejector pins as pressure transfer agents. By substituting an ejector sleeve for the ejector pin, incorporation of the thermocouple with the pressure transducer was possible (Fig 9). The thermocouple was threaded through the sleeve by means of a slot cut in the side of the sleeve. The thermocouple was centered in the sleeve by means of a fixture and bonded in place using a ceramic cement. Several protrusion lengths were to be evaluated ranging from 0.10" to .045".

Proper locations of water lines in an injection mold is very important. Nonuniform cooling of the polymer may result if the line locations are incorrect. This could manifest itself in the molded part by warpage, non-uniform shrinking or cracking. Effort was made to have uniform cooling in the specimen mold by having the lines in the top of the mold mirror the lines in the bottom of the mold. The polymer melt in a cavity will show a temperature gradient with the highest temperature near the gate and

declining toward the edges. Therefore the water lines were located such that the water enters the mold near the gate and exits near the sides.

It would not be good practice to mold both the plaque and flow finger at the same time. The volume differences between the two cavities result in an imbalance in the rate of fill. This imposes additional pressure and temperature fluctuation in the melt which are unpredictable. To prevent this, a shut-off was installed. By proper positioning of the shut-off, either cavity would be in line with the runner system.

Polymer Selection

Investigation of all polymers did not lie within the scope of this program. Thermoplastic polymers fall into either of two groups- crystalline or amorphous. Most polymers are not all amorphous or all crystalline, the degree is dependent on the nature of the polymer. Crystallinity is affected by such processing variables as temperature, cooling rate and time. Studying the effects of processing variables on crystallinity is outside the present scope of the program. Therefore this program was to concentrate on amorphous polymers initially with possible incorporation of crystalline polymers at a later date. The polymers selected for initial study were polystyrene (Dow 666) and polycarbonate (Lexan 141).

Polystyrene was selected primarily because it has been used in other related polymer processing studies. In addition to the polystyrene, the polycarbonate was selected because it is also an amorphous polymer and is widely used for military applications.

Molded Specimen Configurations

It was planned to design a mold cavity configuration from which appropriate mechanical and physical properties could be obtained. The mold design was also dependent upon the material moldability and interface between sensing instruments and molded items.

Since the mechanical and physical properties encompassed tensile impact, shrinkage and birefrigence, the mold cavity should be of a square or rectangular shape as opposed to circular. This configuration would also enable the machining of the tensile impact specimen, 2-1/2 inches long x 3/8 inches wide x 1/16 to 1/4 (1/8 inch preferred) inches thick. Test specimens for birefrigence testing should also be flat with a uniform thickness. Although the molded item or specimen was just a test vehicle, the rules of good mold design must be followed.

The specimen should not be of such a thickness as to cause sink marks and/or internal voids. At the other extreme, it should not be so thin that difficulty in filling would be experienced. If the specimen is too thin, skin or edge effects may have too much influence on the specimen. Since most molded items are rectangular or oval, the specimen should reflect this. The interface between the specimen and sensing instruments could be either curved or flat. A flat surface is preferred because it is easier to locate and machine in the mold. Based on the above, a flat plaque 3" x 5" long x 1/8" thick was selected as the specimen (Fig 10). As previously mentioned, shrinkage measurements were to be taken. Overall shrinkage of the plaque could be measured easily. However it was felt that

measurements in various locations would also be useful. Therefore another cavity plaque insert was designed with scribe marks every 1/2 inch (Fig 11). A visual means of comparing flow behavior is also desired. A flow finger [14] specimen (Fig 12) was designed with each of 8 fingers having a difference thickness. Changes in the apparent viscosity as a result of process variable changes will be seen as changes in the amount of fill in each finger.

Molding Verification

To evaluate the instrumented system all necessary equipment was purchased;all desired tooling was fabricated for preliminary molding. The initial molding with polystyrene was set up using the resin manufacturer's recommended molding conditions as a guide.[15,16] High, middle, and low values of pressure and temperature were selected along with a high and low mold temperature setting. This established 18 sets of conditions (Table 1).

Screw location, pressure and temperature in the nozzle and at each point of interest in the mold were to be recorded on the light beam recorder. With the aid of timing marks on the chart the various traces could be compared at any specific instant in the molding cycle.

The initial set up of the instrumented injection machine and mold revealed the mold and the instrumentation readout system functioned properly. However there was a problem with the machine and with the mold thermocouples. After 4 to 5 hours molding, a discontinuity in the hydraulic trace injection curve was noticed. At about the 3/4 of maximum pressure in the injection curve, the pressure would suddenly drop some 40% and then continue up to peak pressure. This pressure drop involved about

.2 second and showed up as a melt pressure drop at the gate and as a screw travel reverse. What effect this had on the part properties was not known, however molding was stopped when this occurred. It was felt that the problem could be lived with and no immediate attempt was made to discover the cause of the pressure drop.

The thermocouple problem was of greater concern. The initial mold setup contained thermocouples with a .010 inch protrusion. The response from these thermocouples reached a maximum of less than 200°F with nozzle melt temperature about 350°F. The thermocouples were replaced with a .045 protrusion one before the gate and a .024 protrusion one after the gate. Both thermocouples read a high of about 170°F with the nozzle temperature at 350°F. It was postulated that the reason for the inability of the thermocouples to sense temperatures about 200°F lies in the insulating properties of the polymer. As the melt flows past the thermocouple it is rapidly coated with polymer which quickly solidifies. The solidified polymer then acts as an insulator keeping the heat of the flowing polymer away from the thermocouple tip. It was decided to discontinue the effort to measure melt temperature in the cavity and the sleeves were replaced with ejector pins.

The molding of specimens was initiated. A procedure was developed for setting molding conditions. The first setting was mold temperature. Next melt temperature, and then injection pressure was set; the charge weight was then adjusted to give a small cushion. Holding pressure was set to prevent polymer reverse flow from the cavity. Duration of holding pressure was adjusted so that gate "freeze off" occurred before release of holding pressure.

The time was determined by examining the before-and after-gate pressure traces. If, upon removal of pressure, the after-gate trace showed a sharp change in its slope, the time was not long enough. The holding time would be lengthened until pressure release caused no change in the slope of the trace. Once the injection cycle was consistent, thirty consecutive specimens were molded and numbered. A trace was made for each specimen at a speed of .1 in/sec (Fig 13) chart speed. Immediately before and after the thirty specimens, a trace of the cycle from injection to holding pressure release was made at 1 in/sec. chart speed. At the end of each run, a trace from injection to initiation of holding pressure was made at 8 in/sec chart speed. The various recording speeds were a result of efforts to get detailed pressure curves. This procedure was repeated for each run. In order to get each set of specimens approximately 125 specimens were molded.

Testing

Preliminary testing of the molded specimens was conducted to determine the effect the pressure and temperature changes have on properties of the molded specimens. Birefringence techniques were used to compare the stress levels in specimens molded under different molded conditions. Although it is difficult to obtain direct stress level readings by this method, the method is able to provide comparison data between molded specimens. Shrinkage measurements were also used in determing the effects of changes in pressure and changes in the properties of the specimens. Shrinkage measurements were made on the molded specimens both parallel to and perpendicular to the direction of the polymer flow.

An additional technique used in the determination of the effect of changes in pressure and temperature on specimen properties was that of tensile impact testing. Impact specimens were machined from several locations on the molded specimens and subjected to tensile impact testing.

The results of the above described tests indicated that the properties of the molded specimen are affected by changes in molding pressure and temperature. The birefringence testing indicated that changes in molding pressure and temperature caused changes in the stress level in the molded specimen. However an assessment of the degree of difference between molded specimens was beyond the scope of this program. The results of the shrinkage measurements indicated that the amount of shrinkage of the molded specimen was affected by changes in the molding pressure and temperature.

The tensile impact test results showed that changes in molding pressure and temperature did affect the strength of the machined tensile impact specimens.

CONCLUSIONS

Industrial consultations revealed that the effects which processing variables have on the properties of an injection molded item are complicated and still remain difficult to predict exactly. Past experiments in this field have used machine settings for pressure and temperature of the polymer. Actual melt pressure and temperature measurements are now readily obtainable as well as a technique to measure melt pressure in the mold cavity during injection molding.

The use of a high speed recording system enables recording of the pressure curve during the injection molding cycle. An instrumented system to directly record polymer pressure and temperature was developed and determined to be suitable for the intended objective. Trial moldings were conducted with the instrumented injection machine and mold.

The preliminary testing conducted on specimens molded under various molding conditions indicated that the properties of the molded specimen are affected by changes in molding pressure and temperature.

RECOMMENDATIONS

Based on the results described herein, in which it was demonstrated that the effect of process variables on molded specimens can be measured, it is recommended that continued evaluations be conducted considering other materials and variables.

It is recommended that the instrumentation be also utilized in the development of quality assurance methods.

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MOLDING CONDITIONS TABLE

Material - DOW 666 General Purpose Polystyrene

Mold Temperatures 120°F and 160°F

Melt Temperatures 400°F, 500°F, 600°F

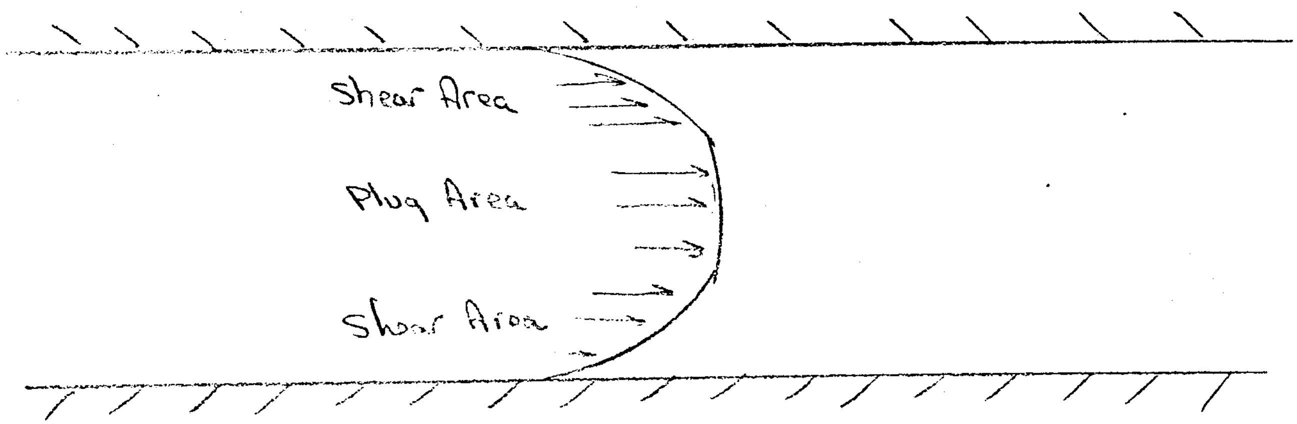
Melt Pressures (Inj.) 10,000 psi, 14,000 psi, 18,000 psi

Material General Electric 141 Polycarbonate

Mold Temperatures 170°F and 250°F

Melt Temperatures 500°F, 550°F, 600°F

Melt Pressures (Inj.) 10,000 psi, 15,000 psi, 20,000 psi



Flow Profile For Plastic Material

FIG 1

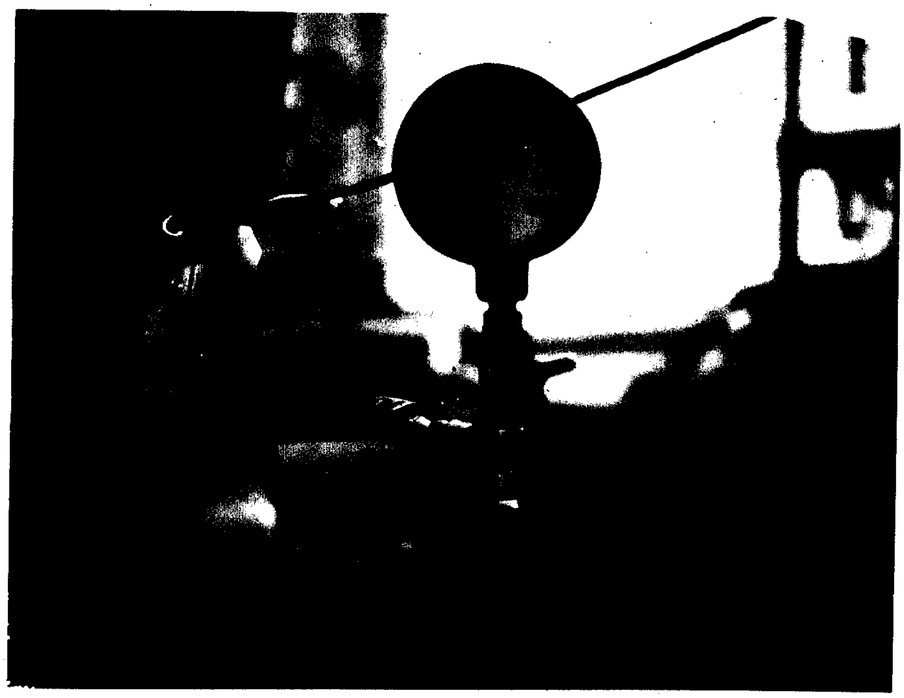


Fig 2 Hydraulic Line Transducer

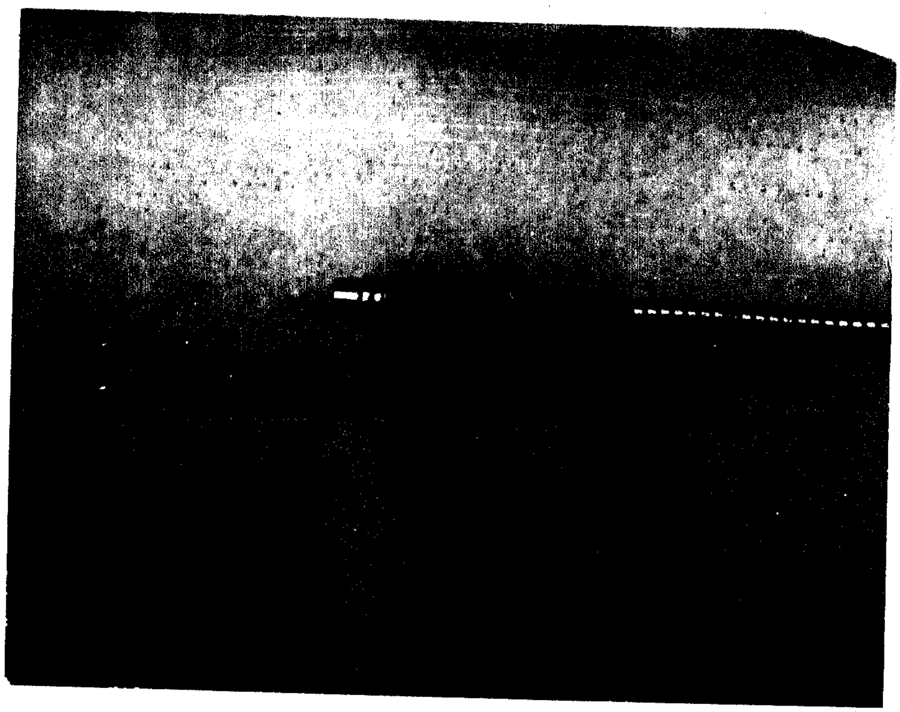


Fig 3 Nozzle Melt Transducer

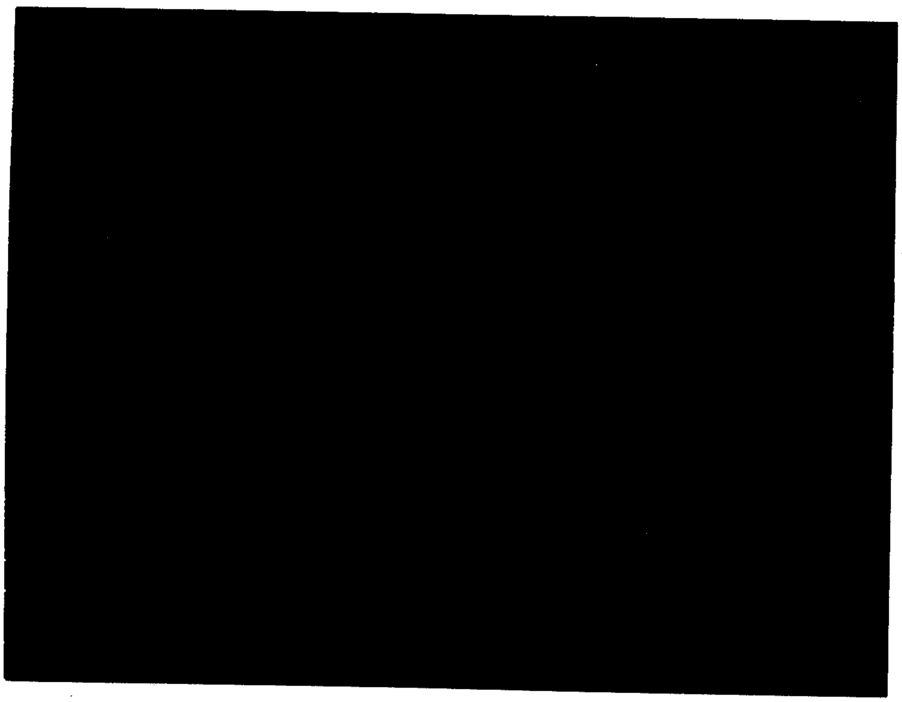


Fig 4 Cavity Transducer

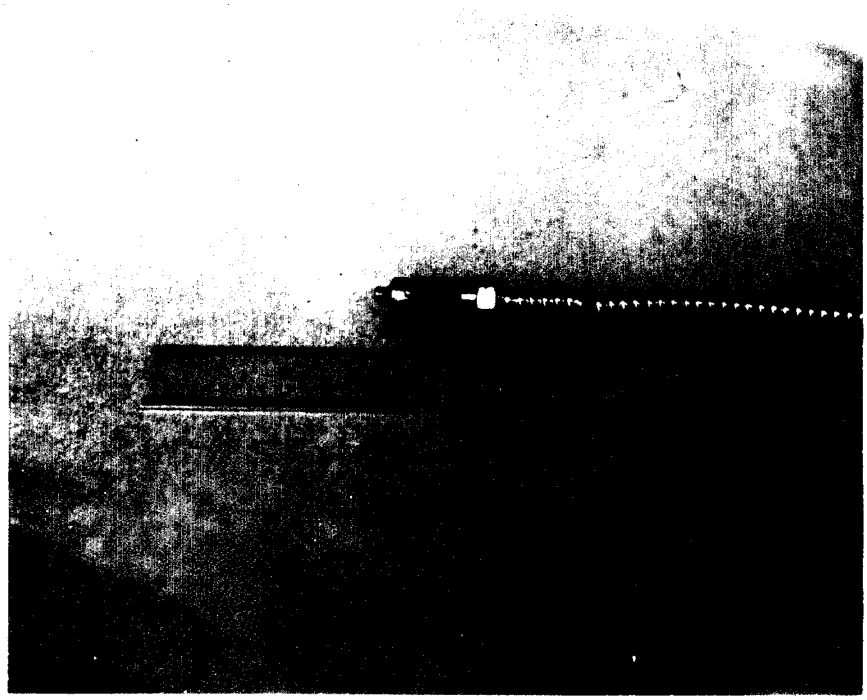


Fig 5 Nozzle Melt Thermocouple

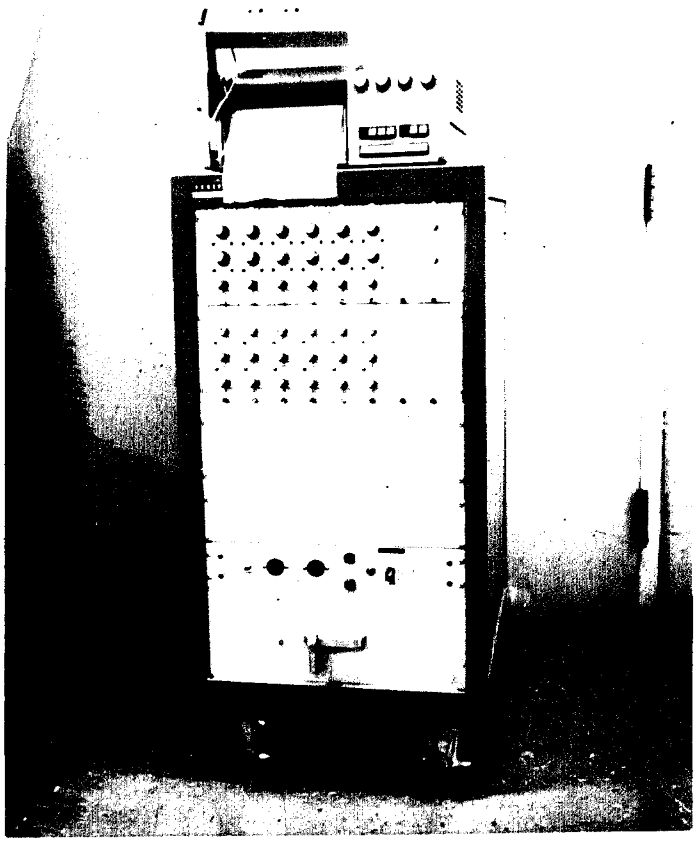


Fig 6 Light Beam Recording System

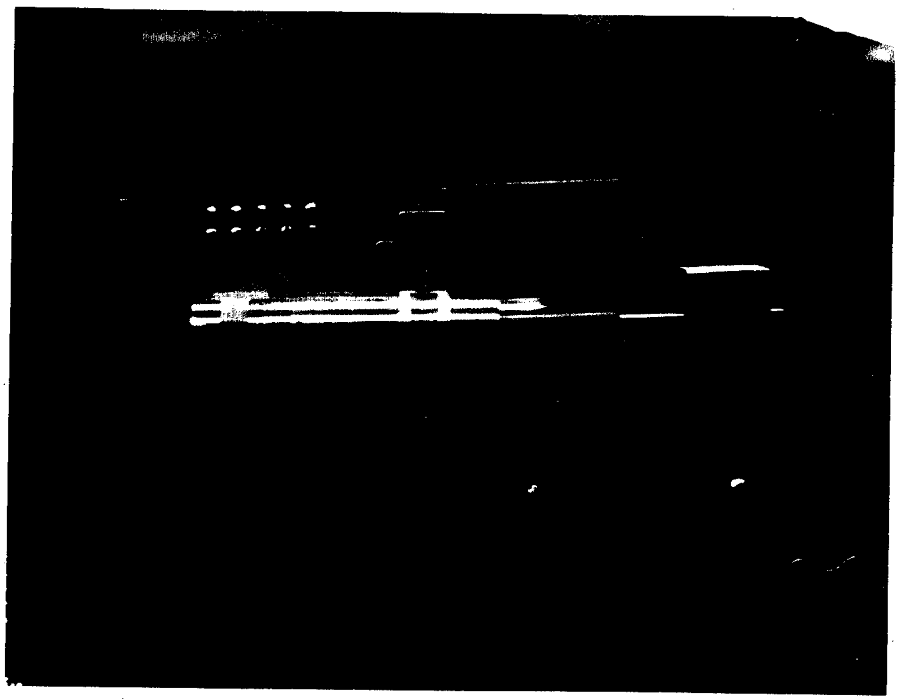
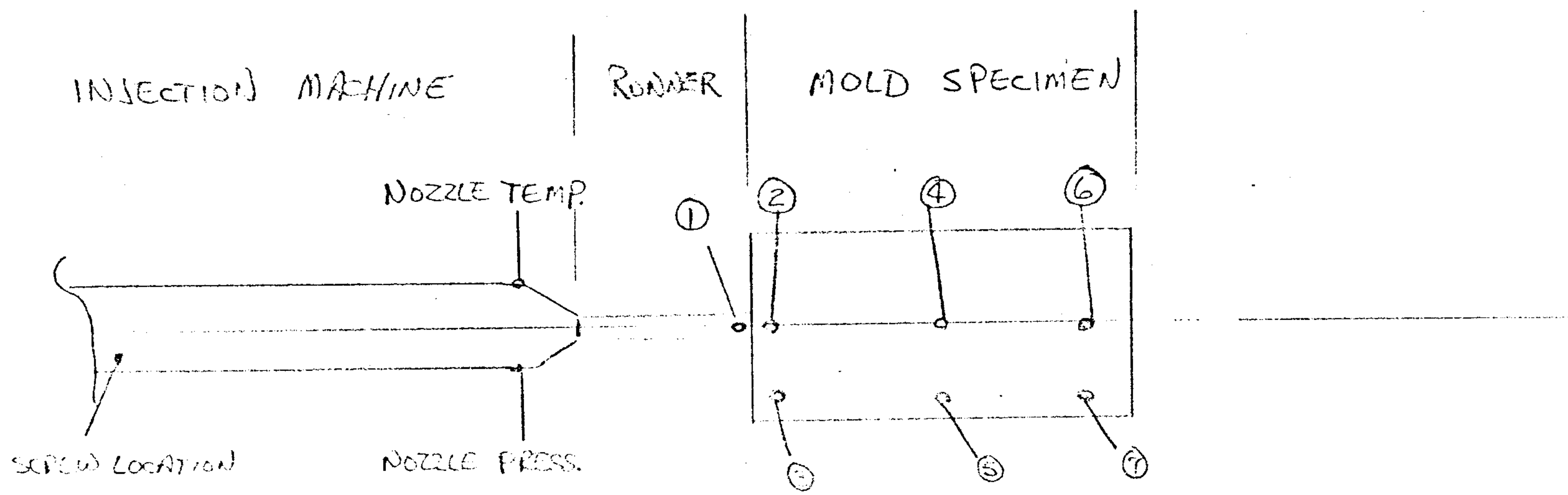


Fig 7 LVDT - Machine Mounted



INSTRUMENT LOCATIONS

Fig 8

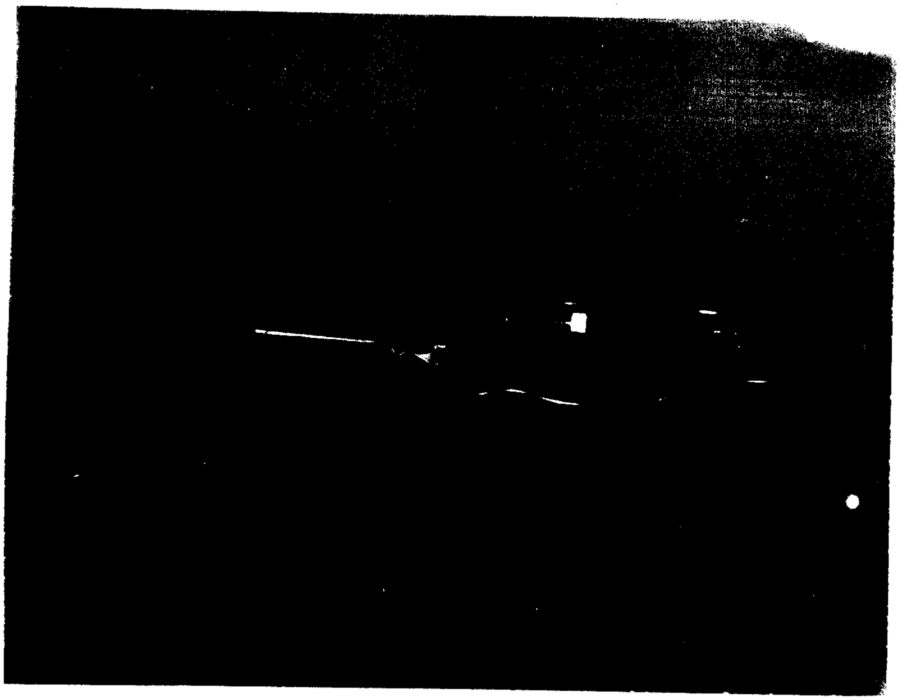
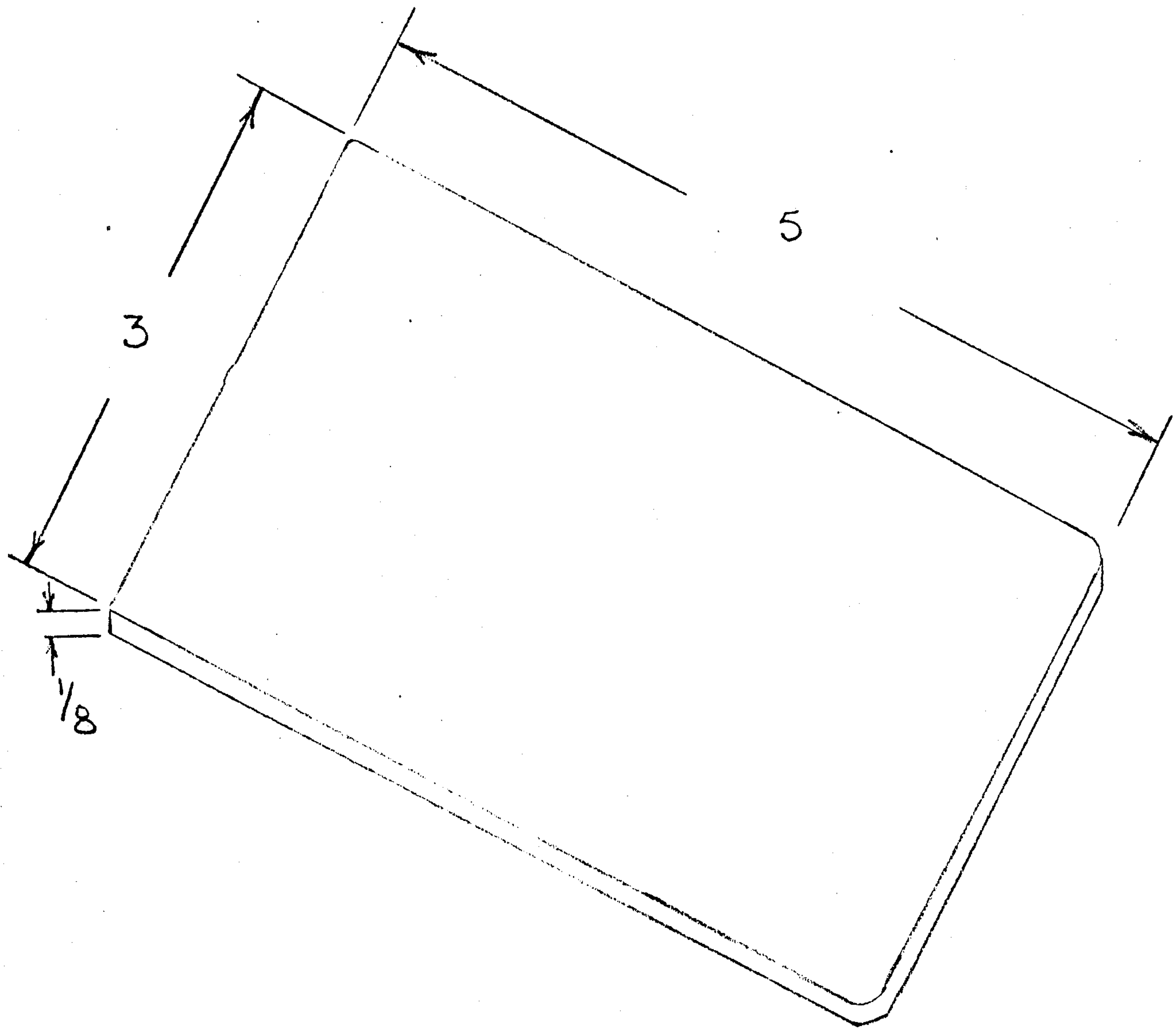
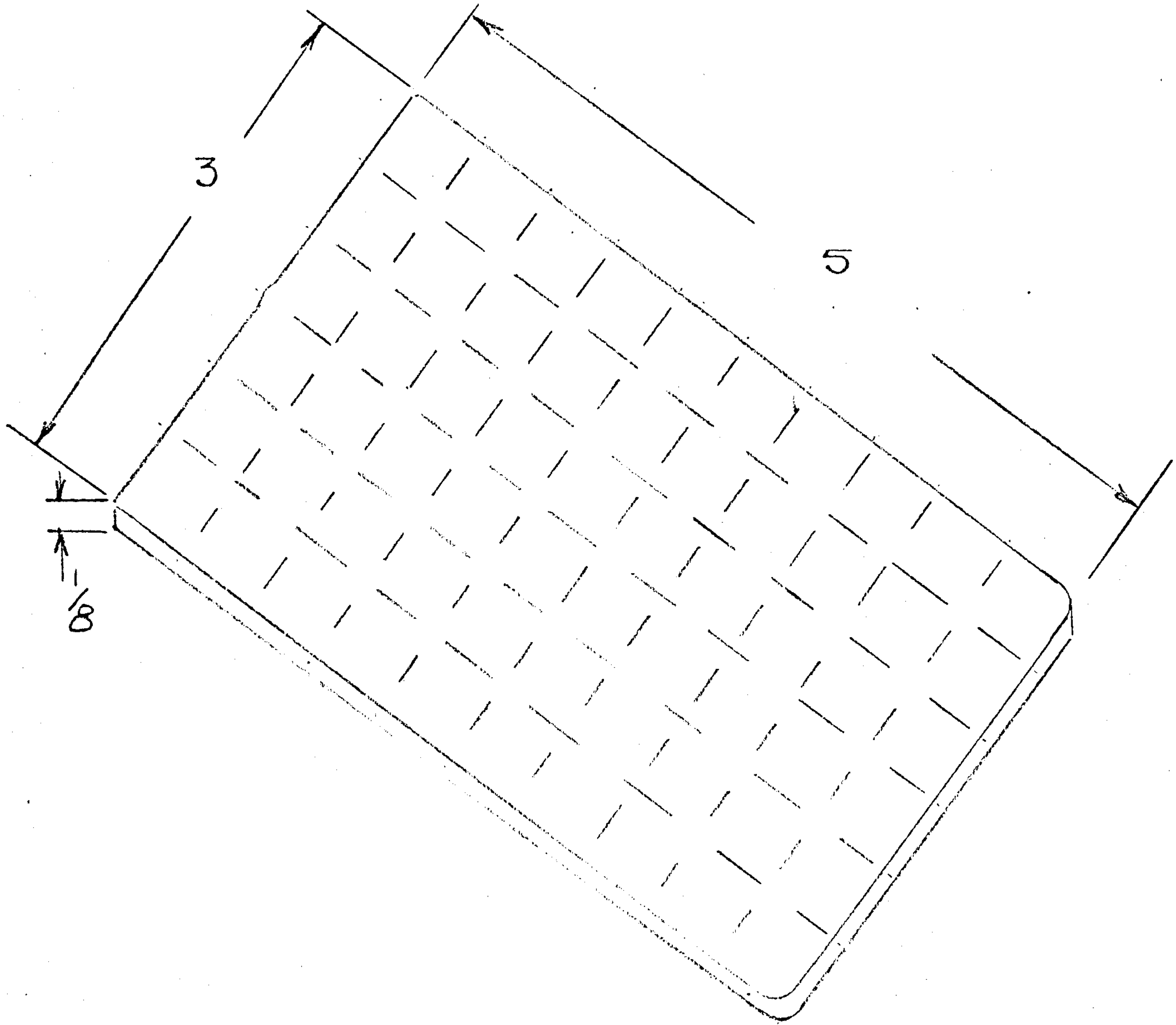


Fig 9 Ejector Sleeve-Thermocouple



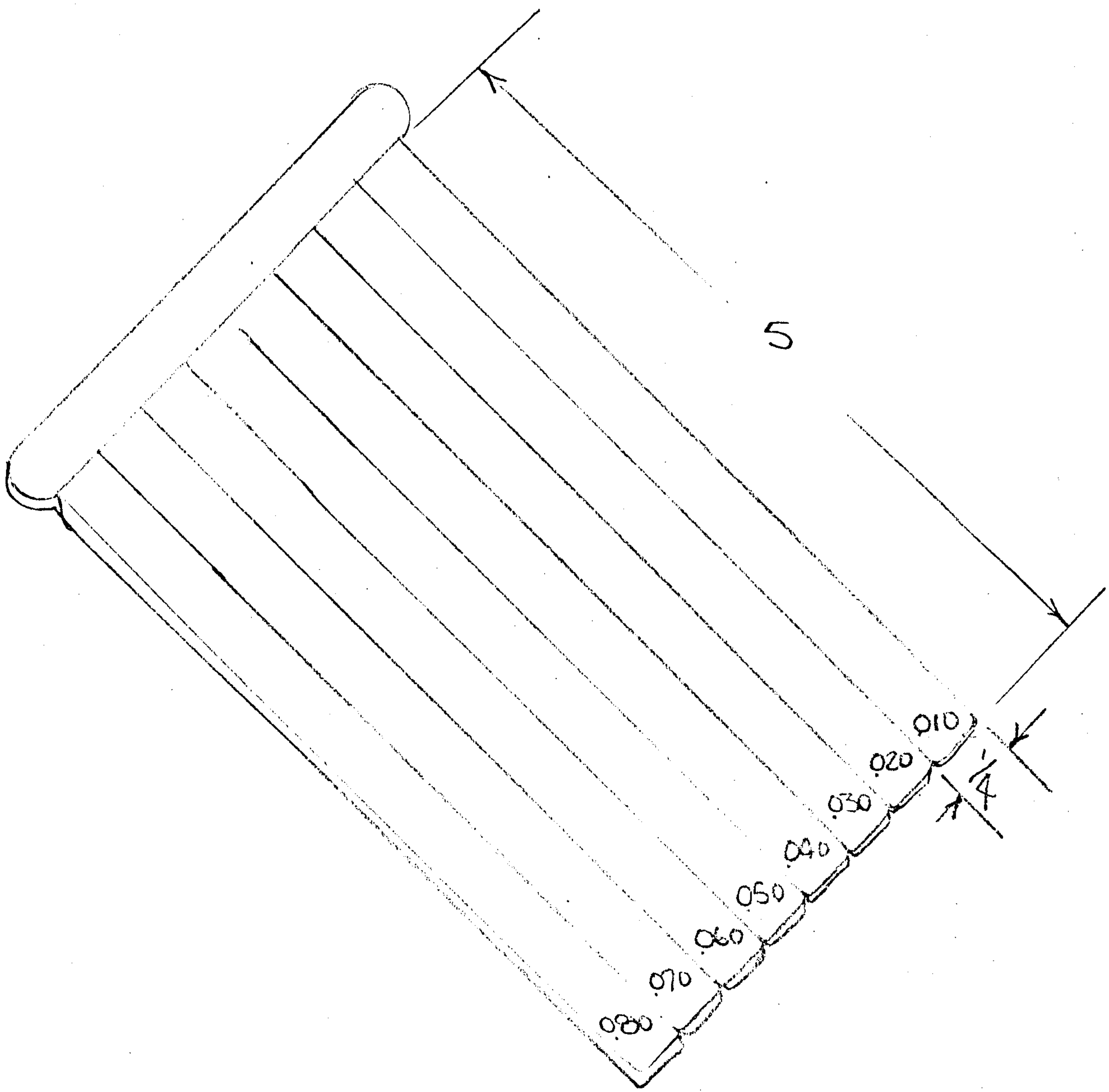
MOLDED SPECIMEN

Fig 10



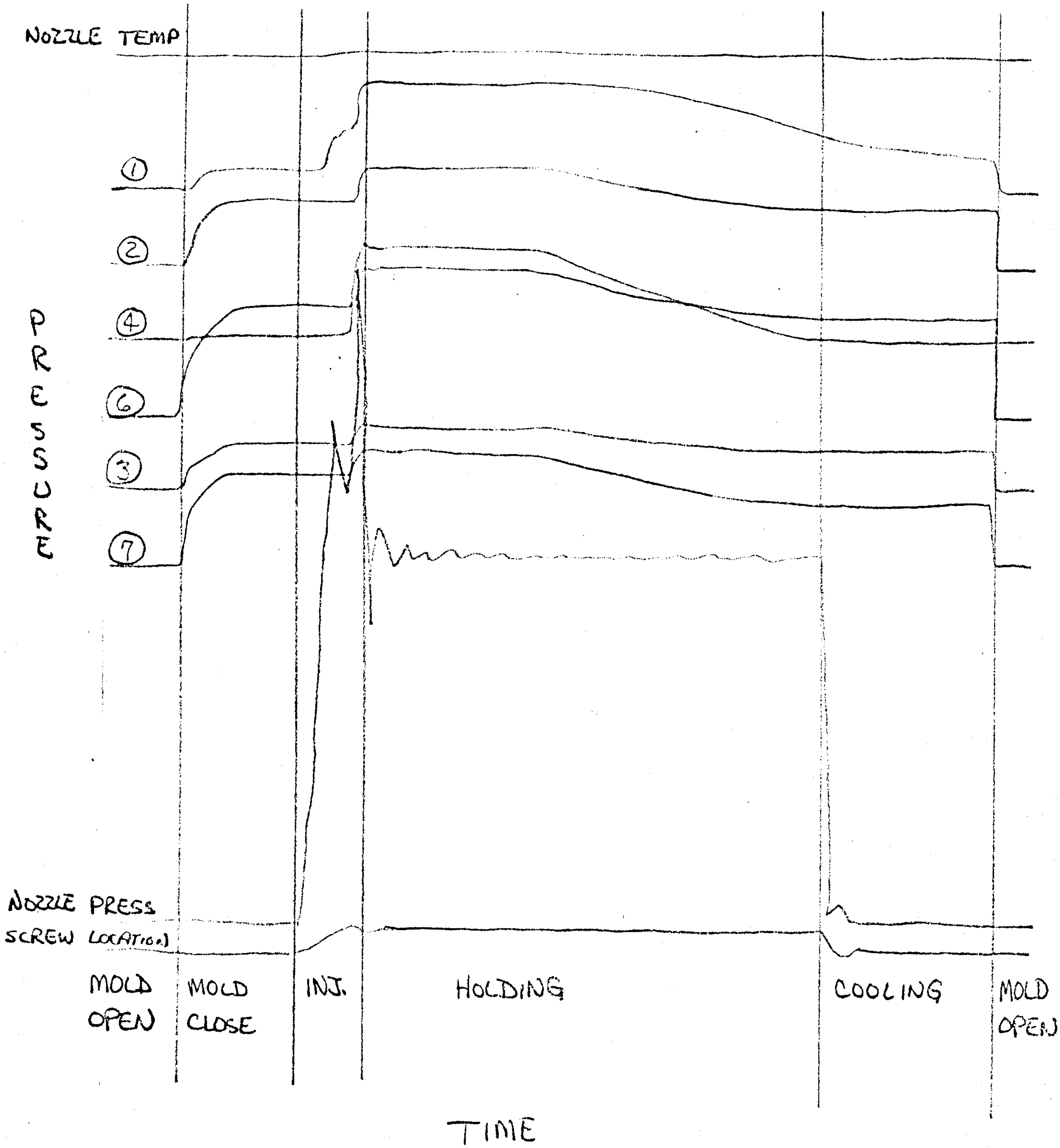
SCRIBED MOLDED SPECIMEN

Fig 11



FLOW FINGER SPECIMEN

Fig 12



TYPICAL MOLDING CURVE

Fig 13

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